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TECHNIQUES FOR OBTAINING SUBJECTIVE RESPONSE TO VERTICAL VIBRATION

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SUMMARY

Laboratory experiments were performed to validate the techniques used for obtaining ratings in the field surveys carried out by the University College of Swansea. In addition, attempts were made to evaluate the basic form of the human response to vibration. The paper describes some of the results obtained by different methods and compares them.

INTRODUCTION

In the summer of 1972 a series of tests was planned for a vertical vibrator then newly installed in the Mechanical Engineering Department, the University College of Swansea. The aim of these tests was to investigate the nature of the subjective response to human beings to vertical vibration over the frequency range from 1 to 70 Hz and over a range of vibration amplitudes corresponding roughly to those recorded in public transport vehicles. In parallel with the laboratory tests a series of questionnaire surveys was being carried out on a variety of transport vehicles in which passenger reaction to the vibratory motion of these vehicles was obtained using rating-line techniques.

Over the years many tests have been carried out to determine human reaction to vibration over all or part of the relevant frequency range. However, the published results show what can only be described as a remarkable inconsistency. The literature up to 1970 has been reviewed by R. M. Hanes (ref. 1) and demonstrates wide variations in reported results. For example, values of sensation threshold for vertical vibration reported by different authors covered a range 1 to 1000 at some frequencies. The differences appear to arise largely from the use of inappropriate, imprecise and sometimes inadequate methods and equipment.

At the time several other workers were known to be beginning research programmes covering similar ground to that proposed by the authors. It was

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felt appropriate to spend time investigating in some detail the experimental methods which would be used, rather than to select a method, carry on with the tests, and possibly produce yet another questionable series of data. In addition a need had arisen for a laboratory survey of rating methods which could be used realistically in questionnaire studies of fare-paying passengers in public service vehicles. This also pointed to a detailed study of methods.

This paper describes some of the experiments conducted and the conclusions which have been drawn about the usefulness of the techniques. It is effectively in two sections with two subsections.

The first section describes in some detail the validation of the rating-line technique which has been used extensively in the questionnaire studies. A brief section then follows describing some experiments designed to test the usefulness of a cross-modality approach, using noise as the matching sensation, for field studies and discusses the reasons why it was abandoned.

The second main section discusses the findings of a short series of experiments in which reaction to vertical motion was investigated using three different psychophysical methods. These were magnitude estimation, fractionation (halving) and multiplication (doubling). The three methods were used to determine exponents for a power-law expression, and the differences in the results obtained are described and discussed. The final section discusses some of the difficulties met in equating sensations across frequencies and indicates a possible way by which they may be overcome.

#### EQUIPMENT

The equipment used for all laboratory experiments, except the cross-modality check, was a Unidyne electrohydraulic actuator capable of achieving  $+0.115\text{m}$  ( $+4.5$  in.) displacement along a vertical axis at low frequencies. The operating boundary was set by a velocity limit of about  $0.5$  m/sec ( $20$  in./sec) at higher frequencies. The usable frequency range extended up to about  $100$  Hz. For the experiments discussed here the operating conditions were kept well within the capabilities of the system.

For the majority of the experiments subjects were standing on a flat plate mounted directly on the top of the actuator. The acceleration of the plate was sensed by a piezoelectric accelerometer mounted directly to the plate beneath the subject's right foot. The accelerometer, calibration table and measuring amplifiers were all Bruel and Kjaer equipment.

For the brief series of cross-modality tests the subjects were seated on an ordinary, adjustable-height, office chair with the balls of their feet resting on a plate driven by a small electromagnetic vibrator. The main weight of the subjects feet and legs was taken on a stationary platform surrounding the plate driven by the shaker.

For all tests the input acceleration waveforms were sinusoidal.

## RATING-LINE METHOD

Several varieties of rating line were used in the questionnaire surveys and are discussed in Osborne and Clarke (refs. 2 and 3). Broadly speaking it was found that the way in which the rating line was divided hardly influenced the results, whereas the effect of the scale ends could be classified in a meaningful way which followed the predictions of intuition or "common sense". A summary of the investigations of these aspects of rating-line techniques is presented elsewhere in this compilation (ref. 4).

The present discussion centers on an attempt to discover just how much information could be obtained from results obtained using an unstandardised rating line. The main points of interest were the repeatability of such ratings and how closely they match similar results obtained by other approaches. Full details of the experiments are given in Osborne and Clarke (ref. 5). This section summarizes that paper.

The rating line used in the experiments is shown in figure 1, together with some information about the test subjects and the test conditions used for the first part of the experiment. The rating lines were presented to the subjects in book form, one line per page, so that each rating was made on a fresh page. Each subject was given the test conditions in a random order. No attempt was made to define the scale ends "smooth" and "rough", nor were any of the test conditions designated as standards. Thus, any standards used in rating judgements were based entirely on the individual subject's background and history and any preconceived ideas he or she may have had about the experiment.

The rating was taken as the distance of the mark in cm from the "smooth" end of the scale. For each test stimulus a mean rating was determined. Figure 2 shows some of the plots of rating against root-mean-square acceleration of the input vibration for specific frequencies. It can be seen that for all stimuli at the same frequency the points plot close to a straight line. The figure includes the best and the worst of the frequency plots, the best being at 11 Hz with a product moment correlation coefficient of 0.999 and the worst being at the ends of the frequency range with correlation coefficients of 0.972 and 0.979 at 3 Hz and 80 Hz respectively. Table I shows the values obtained for the coefficients in the regression equation for the frequencies tested, together with the correlation coefficients.

Figure 3 is obtained from the regression lines, using the argument that equal ratings indicate equal subjective effects. The contours, which are actually equal rating contours, can then be regarded as equal comfort contours or equal reaction contours. The parameters of the contours are specific distances along the rating line. Some indication of the validity of this assumption is gained from examination of figure 4 which shows the curves of figure 3 compared with typical results obtained by two other investigators, Chaney (ref. 6) and Jones and Saunders (ref. 7). It is seen that the shapes of the contours obtained using the rating lines agree fairly well with both of these other curves. It is useful to note that the Chaney curve was obtained by

asking subjects to indicate when a vibration had reached a "mildly annoying" level, whereas Jones and Saunders asked subjects to adjust variable stimuli to a reference vibration at 20 Hz. The agreement looks good, at least good enough to justify further development of the unstandardised rating-line approach. For interest's sake the ISO 1 minute reduced-comfort boundary is also indicated (ref. 8).

#### COMBINATION OF LINE RATINGS WITH SEMANTIC SCALES

The next stage in the test process was to relate the rating contours to other measures of subjective reaction, bearing in mind the fact that the intention was to use such rating lines in field studies. It was decided to investigate the relationship between such line ratings and ratings obtained on a six-point category scale. Figure 5 shows the categories chosen for the test, together with some basic information about the subjects and stimuli used.

Each subject gave a rating of each stimulus on the six-point comfort scale. Each stimulus was allocated the label given most frequently. Fifteen of the stimuli received nearly equal numbers of votes for two categories. These were left out of the subsequent analysis.

The stimuli were then grouped into the appropriate categories. For all the stimuli in a particular category the mean and standard deviation of the line ratings were found. Each category was then arbitrarily assigned a range of line ratings corresponding to one standard deviation on either side of the appropriate mean. The original rating line was thus divided into regions corresponding to the six comfort descriptors. The results are shown in figure 5.

The first point to note is that the two central categories ("fairly comfortable" and "fairly uncomfortable") can be coalesced into one since the overlap is so great. Second, but not unexpectedly in view of the small number of subjects used, there are overlaps and gaps in the groups. These were closed by halving the overlap or underlap to give a contiguous set of categories on the line. Since the boundaries of the categories were defined in terms of distances along the rating line, it was possible to obtain equal-sensation contours which indicated the boundaries of the descriptive zones. The final boundaries arrived at are shown in figure 6 with the positions of the indecisive stimuli indicated.

The final test in the sequence repeated the last stage except that the subjects were given definitions for the categories. Instead of being given just the bare list of categories, they were given a sentence or two of explanation for each category. Since the basic idea of the series of tests was to investigate a technique for use in vehicle studies in the field, the definitions were related to some aspect of travel, and travel time was the one that was actually chosen. Table 2 gives the category descriptors and summaries of the definitions used, and figure 7 shows the final contours obtained. In view of the overlap in the two central categories of the six-point

word scale in part II, the scale was collapsed into a five-point scale which suited the choice of definitions very nicely. It can be seen that the use of defined categories has reduced the number of indecisive inputs by 50%, and by comparison with figure 6 it can be seen that the category boundaries are almost the same, the readjustments being relatively minor.

The work just described, which was conducted entirely in a laboratory, was followed by the use of the rating scales and techniques discussed here in a field study. This is described in some detail, together with some of the results, in another paper in this Symposium (ref. 4).

#### CROSS-MODALITY MATCHING OF NOISE AGAINST VIBRATION

Several times in the literature the suggestion has been made that an ideal way of obtaining the reaction of subjects to ride vibration is to use a method which involves the matching of an adjustable noise stimulus with the sensation of the ride perceived by the subject or passenger. This approach has a lot to recommend it since it is relatively easy to apply a noise stimulus using, for example, a standard audiometer such as is used for audiological screening.

It was decided that tests were necessary to discover how well subjects could match noise to vibration in relatively quiet laboratory situations and in circumstances similar to those which would be encountered in a typical passenger vehicle. Since some recordings of noise had been made in a passenger train, it was decided to use these to provide the background noise for the tests which required this.

The noise to be used for matching was provided by a standard audiometer. To test the effect of different sounds as matching media, three different types of acoustic noise were used. These were pure tones at 250 Hz and 1000 Hz and a broad band low frequency noise with all frequencies up to 200 Hz present. The noise levels could be adjusted in steps of 5dB, which was the standard step for the screening audiometer used.

Individual thresholds of hearing were determined for each of the three noise types. These were used as the appropriate datum points, so that comparisons were being made between vibration levels and matched noise levels above individual thresholds. Individual thresholds were used for correction since a degree of intersubject variation was present.

Figure 8 shows the results for the three noise types. A reasonable regression line was obtained from these results, bearing in mind that only twelve subjects were used. There is no significant difference between the results for the three types of noise used. Thus, provided corrections are made for individual subject thresholds, a good match can be obtained subjectively by using noise as a medium for rating vibration.

A test was then carried out in background noise. The noise used was provided by a recording of train noise played back to give a level of 75 dB(A) at the subject's head. For comparison the level at the subject's head during the "no noise" trials was 55 dB(A). Since there was no difference between the results obtained using three different stimuli in the no background noise situation, only the 1000 Hz tone was used for this trial.

Figure 9 shows the results. Two points are immediately obvious. The first is that the results with and without background noise are similar in shape, but that the results with background noise lie below those without background noise. However, the difference between the two levels is not constant, nor is it particularly consistent, so that corrections would be difficult, particularly in view of the fact that the corrections are of the same order of magnitude as the measured values.

It was decided at this stage to abandon the use of cross-modality matching against noise as a field technique because of these inconsistencies. It would appear, however, that this technique would work well in a controlled laboratory situation.

#### DETERMINATION OF THE EXPONENT IN A POWER-LAW REPRESENTATION OF SUBJECTIVE REACTION TO VIBRATION

For many years investigators have been obtaining curves which show how the physical measures of vibration intensity vary across the frequency range to produce equality of sensation. The different equal-sensation contours were generally described by using relatively vague semantic terms. Some attempts have been made to provide a combination formula to enable both frequency and level of vibration to be taken into account, but these had provided largely inconsistent results.

Stevens (ref. 9) has proposed that for all sensations which may be described in terms of their intensity, rather than quality, a very simple power law related the subjective sensation to the physical excitation. This law is expressed as  $\psi = k\phi^n$  where  $\psi$  is the subjective magnitude,  $\phi$  is the physical magnitude,  $n$  is the power-law exponent and  $k$  is a constant, which depends on the units used. He has determined values of the exponent  $n$  for many sensory modalities but not for whole-body vibration.

It was to be expected that if this law was valid for such sensations as light brightness, light colour, loudness of noise, touch and tactile vibratory sensation, then it would hold for whole-body vibration. Here  $\phi$  would conveniently be taken as the root-mean-square acceleration of the vibration excitation, and in parallel with well-documented results from other modalities, it could be expected that the exponent  $n$  would vary somewhat with frequency.

Stevens has used various techniques for establishing the appropriate values of the constants in the power-law expression but had largely concentrated

on magnitude estimation or on fractionation/multiplication methods. In using the magnitude estimation method the subject is exposed first to a standard stimulus and instructed to consider it as having a magnitude of 10. The subject is then given the test stimulus and is asked for a numerical assessment. For the fractionation method the subject is provided alternately with a standard stimulus and a variable one and is asked to adjust the variable one to provide half the sensation of the standard.

Shoenberger and Harris (ref. 10) carried out the first well-documented, systematic attempt to evaluate the effect of change in physical level of whole-body vibration at a constant frequency on subjective sensation. They produced some reasonably consistent results by using the technique of magnitude estimation. However, their group of subjects was made up entirely of physically fit U.S. Air Force personnel, all of whom had previous experience of vibration experiments. In addition, the method of magnitude estimation had recently been attacked by Poulton (ref. 11) on the grounds, among others, that results obtained by this method appeared to be influenced heavily by the intensity range of variables used in the experiment. Although Shoenberger and Harris listed Poulton's paper in their references, they did not appear to take his comments into account.

An experiment was designed to see whether the results shown in reference 10 could be reproduced consistently using a range of subject types, including some women, and to see whether Poulton's strictures were valid. For this purpose the exponents for a range of frequencies of vibration were to be established using magnitude estimation, fractionation (halving) and multiplication (doubling) techniques. The results are shown in table 3 and in figures 10 and 11.

Table 3 shows the results of using the three methods to determine exponents for six of the frequencies investigated. The subject group sizes were 12 for the magnitude estimation experiments and 8 for the halving and doubling experiments. The exponents quoted are appropriate mean values of the individual results. It can be seen that there are clear differences between the exponents obtained by the three methods. The results using halving and doubling, although different from each other are consistently higher than those obtained using a magnitude estimation technique. The questions then arose as to which was the appropriate value to take or how one averaged the different results to obtain an adequate result.

Figures 10 and 11 show in more detail the results obtained for the frequencies of 7 Hz and 50 Hz, respectively. Figures 10(a) and 11(a) show plots of assessed magnitude against root-mean-square acceleration on log-log scales, so that the exponent is the slope of the best straight line through the data. Figures 10(b) and 11(b) show plots of the standard stimulus against the stimulus assessed by the subject as providing half the sensation provided by the standard. From the slopes of these plots the exponents can be determined using the expression  $n = \log 2 / \log (\text{slope})$ .

Looking first at figures 10(a) and 11(a) several interesting points stand out. First, the mean values of each set of data appear to lie consistently on

a curve, one which is admittedly not too distant from a straight line. Second, the standard stimulus, if plotted, lies consistently below the best straight line in such a way that if the standard is included as a data point, the curve is a cusped curve showing two loops. Third, the scatter of the data points increases consistently as the stimulus moves away from the standard. Closer investigation of the lines and data points provided by Shoenberger and Harris in their paper and insertion of their standards on the figures indicate exactly the same trends, save that they quote no value for scatter. These effects are, roughly speaking, those predicted by Poulton and they form the basis of his assertion that determined exponents can be made to have values over a fairly wide range by careful choice of the range of experimental values.

Looking at figures 10(b) and 11(b) two indications appear. First, the median values for each stimulus lie almost exactly on a straight line for the two examples, as is the case with all sets of results. Second, the scatter is significantly less than that obtained with the magnitude estimation results. In this connection it should be noted that very precise exponents can be obtained by fractionation, the range obtained for a given frequency covering a ratio of 1.25 to 1.00 for individual exponents. This compares favorably with a ratio of 2 to 1 or 3 to 1 for exponents for individuals obtained by magnitude estimation.

Similar considerations apply to the results obtained using the doubling method except that the scatter is greater than the scatter for results from halving while still being considerably less than that for results obtained by magnitude estimation.

Part of the difference between exponents obtained by halving and by doubling could be explained by a time effect. This effect is such that in many psychophysical experiments in which two stimuli are matched one against the other, there is a consistent bias in the level of the second stimulus. The indications here are that the second stimulus is consistently matched high; some experiments in which a subject was asked to equate two vibrations at the same frequency produced matching responses consistently about 10 percent higher than the standard. This would account for a large part of the difference between the slope obtained by halving and by doubling and would also account for the standard in magnitude estimation results being consistently below the line.

It seems appropriate to take the mean of the halving and doubling results to correct for this effect. If this is done the resulting exponent is still higher than that obtained from magnitude estimation.

An appropriate way of checking the correctness of the exponents is to select from a set of equal-sensation contours one to be used as a datum, and to use the power law with appropriate exponents to predict the other equal-sensation curves. Using this procedure Shoenberger and Harris obtained fair agreement between predicted and determined contours. Even better agreement is obtained if the exponents produced by averaging the halving and doubling results, as discussed here, are used. Checks on some other experimental data give the same result. Unfortunately the work had to be discontinued at this

point, and time and manpower have not yet enabled it to be picked up again.

#### DEFINITION OF EQUAL-SENSATION CONTOURS FOR SINUSOIDAL INPUTS

The last section referred to equal-sensation contours for vibration responses at different frequencies. Although many investigators have been producing such contours in recent years, the tragedy is that there is still disagreement as to the basic shapes of the curves in that there appear to be two groups of results. These will not be discussed here since they have been extensively discussed elsewhere (see, for example, ref. 12).

Some experiments were carried out at Swansea to obtain equal-sensation contours to be used with results for exponents such as those discussed in the previous section. The method used was the now standard technique whereby vibration at an appropriate level at some arbitrarily chosen standard frequency is matched by sensations from vibrations over a range of frequencies. Reasonable results were obtained, but it became increasingly obvious that subjects did not enjoy matching vibrations at 2Hz with vibrations at 10 Hz for example, because of the differences in the sensations. Accordingly, it was felt that matching vibration sensation would be easier if a sequence of standards was used, stepping across the frequency range in short steps.

A student in the Department of Psychology at Swansea was given the task of investigating this method whereby the matching is always done using adjacent frequencies in the range of values being investigated (ref. 13). The result of one rating becomes the "standard" for the next, and so on until by this monotonic stepping process the frequency range of interest is covered. As a check the process is then reversed and the frequency range traversed back to the beginning. Ideally, the curves obtained from increasing and decreasing frequencies should coincide and the final point should be the same as the starting point.

Figure 12 shows two sets of test data from the 14 obtained. It can be seen that the match between the curves for increasing and decreasing frequencies is fairly good. The two curves shown are typical of all the results in that the 14 curves obtained fall roughly into two groups. In one there is fairly marked frequency dependence, particularly for the higher frequencies. In the other the curves are fairly flat in terms of frequency dependence. These two types of individual response curves match roughly the two types of group data which have been published.

Finally figure 13 shows a plot of the curve of the means of the 14 subjects (each providing two points at each frequency), together with the scatter band.

## CONCLUDING REMARKS

Experiments are described which were designed to test the efficiency of methods which could be used to obtain human response to vibration inputs, particularly in passenger vehicle situations.

The rating-line method, which had been found to be one of the most easily used in field situations, was used to generate equal sensation contours whose shapes matched those obtained by other methods. The numerical values of line ratings have not, so far, been linked directly with numerical estimates of intensity obtained by, for example, magnitude estimation methods.

The use of magnitude estimation techniques was examined in some detail in view of criticisms made by Poulton and others and in view of the fact that many investigators were beginning to use these techniques for obtaining subjective reactions to vibration. It was found that, for situations where they could be used, the methods of halving and doubling gave consistently different results with higher exponents for a power-law expression than those provided by magnitude estimation. From an engineering point of view the indication is that magnitude estimation results are probably not conservative and should, therefore, be viewed with caution.

## ACKNOWLEDGEMENTS

Thanks are due to the Science Research Council of Great Britain for financial support, to Dr. M. McCullough for his work on the psychophysical aspects of the study, to those who consented to act as subjects, to D. A. Humphries for permission to quote from his thesis and to Professor C. E. M. Hansel and Professor F. T. Barwell of the University College of Swansea for advice and support.

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TABLE 1. - VALUES OF REGRESSION EQUATION COEFFICIENTS AND CORRELATION COEFFICIENTS OBTAINED FOR FREQUENCIES TESTED

[Rating = aX + b      X = rms acceleration in m/sec<sup>2</sup>]

Frequency, Hz	a	b	Correlation coefficients
3	5.525	5.167	0.972
5	6.592	5.864	0.985
7	5.676	5.530	0.996
9	5.493	5.044	0.997
11	6.224	4.647	0.999
15	5.771	4.536	0.998
20	5.126	4.155	0.996
30	5.655	3.124	0.989
40	5.579	2.279	0.990
60	3.930	1.763	0.988
80	3.880	1.699	0.979

TABLE 2. - DEFINITIONS USED FOR DESCRIPTORS FOR PART III OF STUDY

[Seven undergraduates (different from those of part II) were used as test subjects for part III; seventy-five stimuli (identical to those of part II) were used]

<u>Descriptor</u>	<u>Definition</u>
Very comfortable	For a long journey
Comfortable	For a journey of about 1 1/2 hours
Just comfortable	For a journey of not more than 1/2 hour
Uncomfortable	Only if the journey was very short
Very uncomfortable	Would not use this form of transport

TABLE 3. - POWER-LAW EXPONENTS BY EXPERIMENT

Frequency, Hz	Magnitude Estimation	Fractionation Method	
		Halving	Doubling
3	1.08	1.24	1.51
5	1.08	0.99	1.46
7	0.94	0.98	1.28
20	0.90	0.79	1.12
30	0.78	0.78	1.54
50	0.82	0.96	—

TEST SUBJECTS 12 UNDERGRADUATES

TEST STIMULI 75 SINUSOIDAL VERTICAL VIBRATIONS  
PRESENTED IN RANDOM ORDER WITH 11 FIXED  
FREQUENCIES (3-80 Hz) AND AMPLITUDES  
RANGING FROM WEAK TO STRONG

RATING LINE

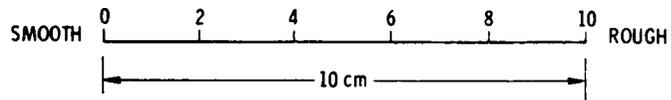


Figure 1.- Rating line used, together with details of subjects and stimuli for part I of present study.

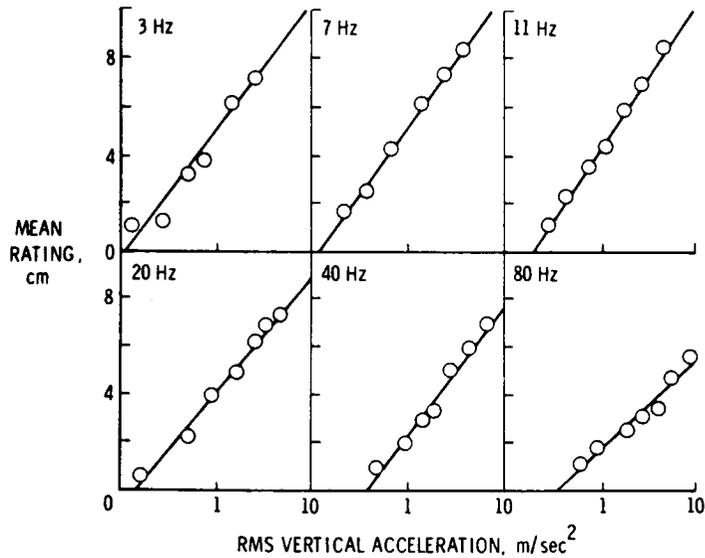


Figure 2.- Plots of mean rating against vibration level for six of the frequencies used, together with relevant regression lines.

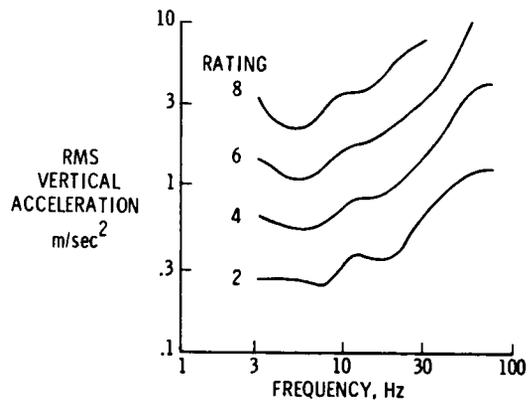


Figure 3.- Equal rating contours (equal comfort contours).

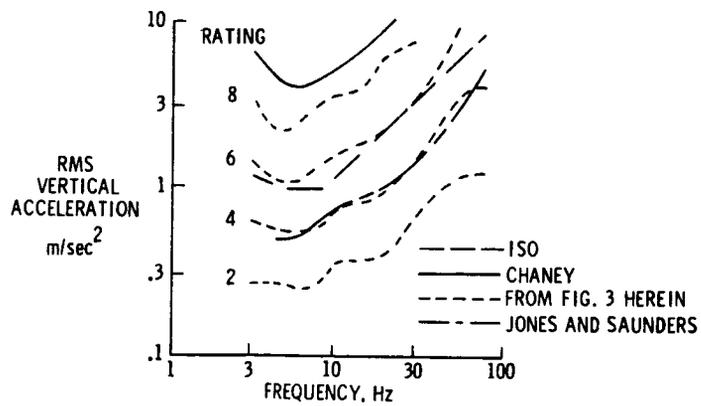


Figure 4.- Comparison of equal rating contours of present paper with results of Chaney and Jones and Saunders and with the ISO 1 minute reduced-comfort boundary.

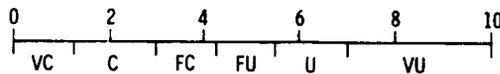
TEST SUBJECTS: 7 UNDERGRUATES

TEST STIMULI: 75 STIMULI (IDENTICAL TO PART I)

RESPONSE DESCRIPTORS: VERY COMFORTABLE (VC)  
 COMFORTABLE (C)  
 FAIRLY COMFORTABLE (FC)  
 FAIRLY UNCOMFORTABLE (FU)  
 UNCOMFORTABLE (U)  
 VERY UNCOMFORTABLE (VU)

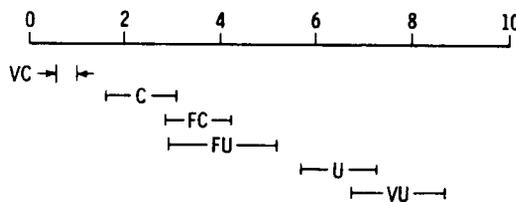
OBJECTIVE

DIRECTLY RELATE RESPONSE DESCRIPTORS TO RATING-LINE VALUES



RESULTS

OVERLAP OF DESCRIPTOR ZONES AND INCOMPLETE RANGE COVERAGE



(EACH ZONE WIDTH IS MEAN RATING ± 1 STANDARD DEVIATION)

Figure 5.- Results of matching semantic descriptions of vibration stimuli with ranges of rating-line responses, together with details of subjects and stimuli, for part II of present study.

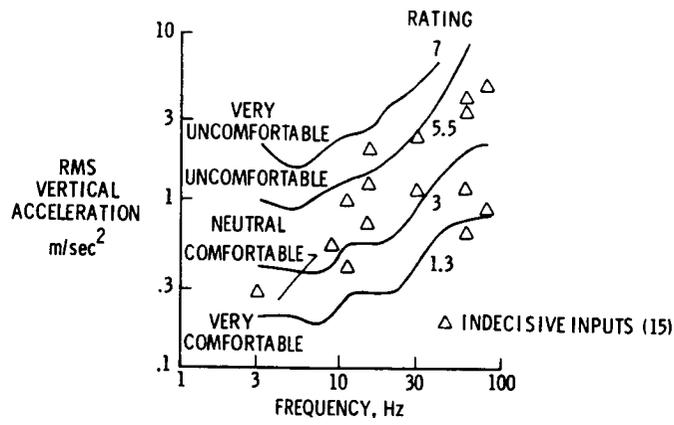


Figure 6.- Equal comfort zones obtained using undefined descriptors.

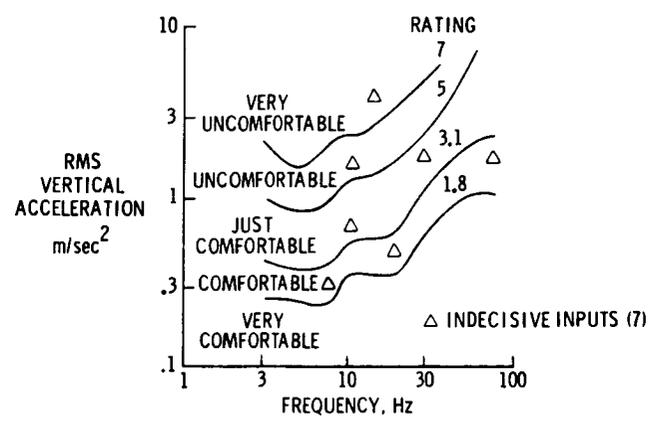


Figure 7.- Results of matching semantic descriptions of vibration stimuli, using defined categories, with ranges of rating-line responses.

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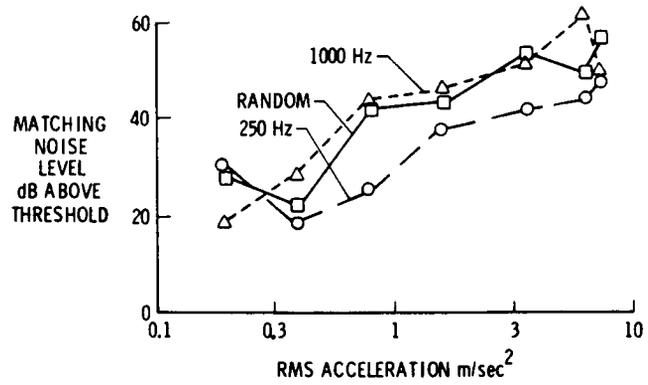


Figure 8.- Cross-modality match of noise level with vibration. (Average of 12 test subjects.)

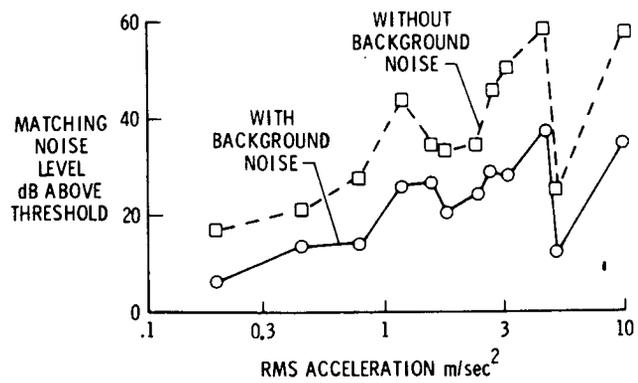


Figure 9.- Effect of background noise on cross-modality matching of vibration with 1000 Hz tone.

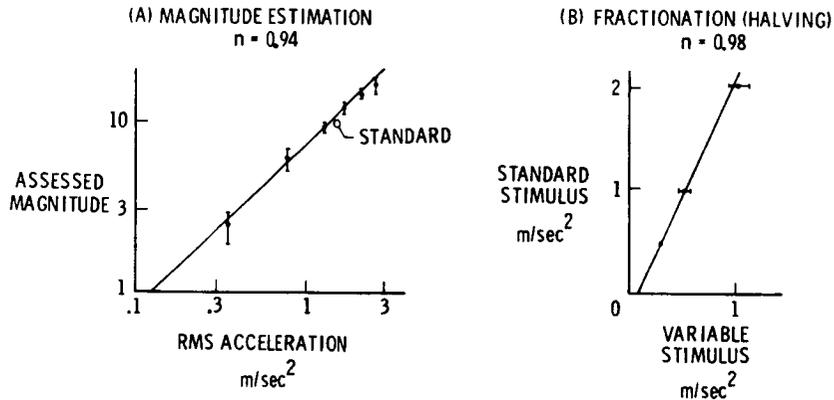


Figure 10.- Results for tests at 7 Hz with magnitude estimation and fractionation.

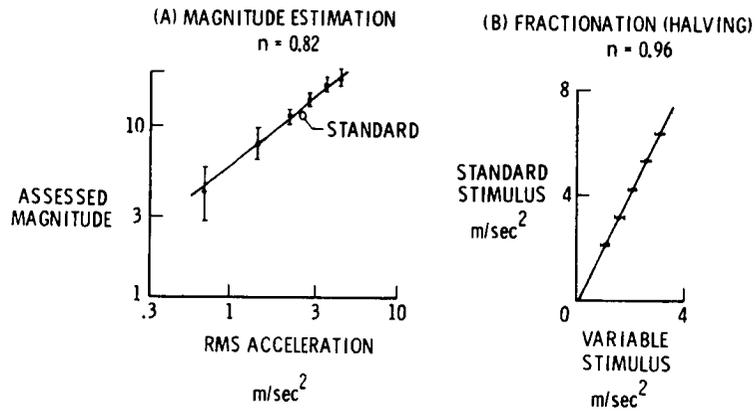


Figure 11.- Results for tests at 50 Hz with magnitude estimation and fractionation.

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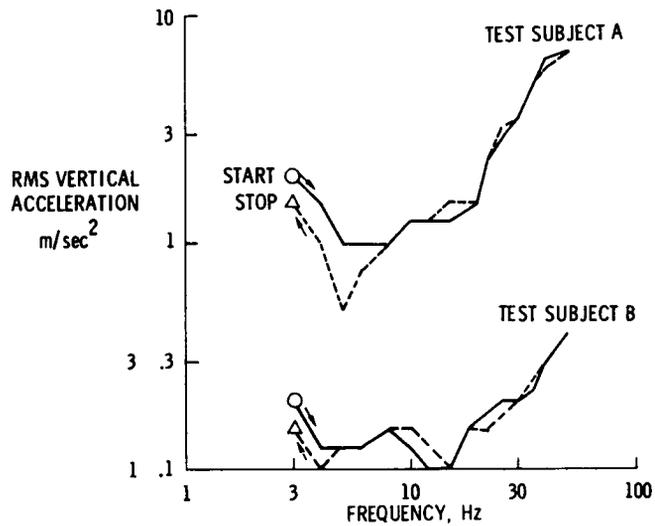


Figure 12.- Typical individual results obtained by progressive matching. (Leftmost scale is for subject B.)

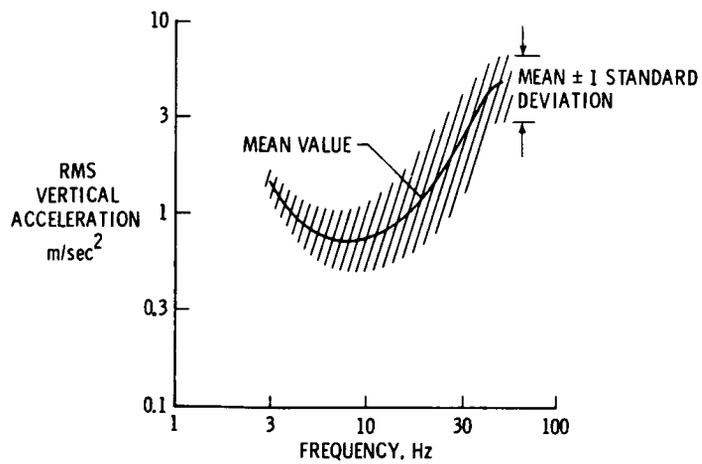


Figure 13.- Average results for 14 subjects obtained by progressive matching.